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The Development of a Lagrangian Cloud Microphysics Package in HiGrad for the Simulation of Pyrocumulonimbus (PyroCb) Clouds

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10/07/2021

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The Development of a Lagrangian Cloud Microphysics Package in HiGrad for the Simulation of PyroCumulonimbus (PyroCb) Clouds

01 **Introduction to HiGrad**

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Introduction to HiGrad: High Gradient Model

- Developed at LANL for over 20 years
- Includes several modules and subroutines to model:
  - Clouds
  - Hurricanes
  - Wildfire-atmosphere interactions (when coupled with FIRETEC)
  - Explosives behavior
- Solves compressible Euler equations in 3-space in generalized coordinates

Conservation of mass, momentum, energy:

$$\partial_t \mathbf{u}(x,t) + \partial_x \mathbf{F}(\mathbf{u}(x,t)) = 0, \quad x \in \mathcal{I}, \ \ t > 0,$$

$$\mathbf{u}(x,0) = \mathbf{u}_0(x), \quad x \in \mathcal{I}, \ \ t = 0,$$

$$\mathbf{u} = \begin{pmatrix} \rho \\ m \\ E \end{pmatrix} \text{ and } \mathbf{F}(\mathbf{u}) = \begin{pmatrix} m \\ \frac{m^2}{\rho} + p \\ \frac{m}{\rho}(E+p) \end{pmatrix}$$

and

$$\mathbf{u}_0(x) = \begin{pmatrix} \rho_0(x) \\ m_0(x) \\ E_0(x) \end{pmatrix}$$

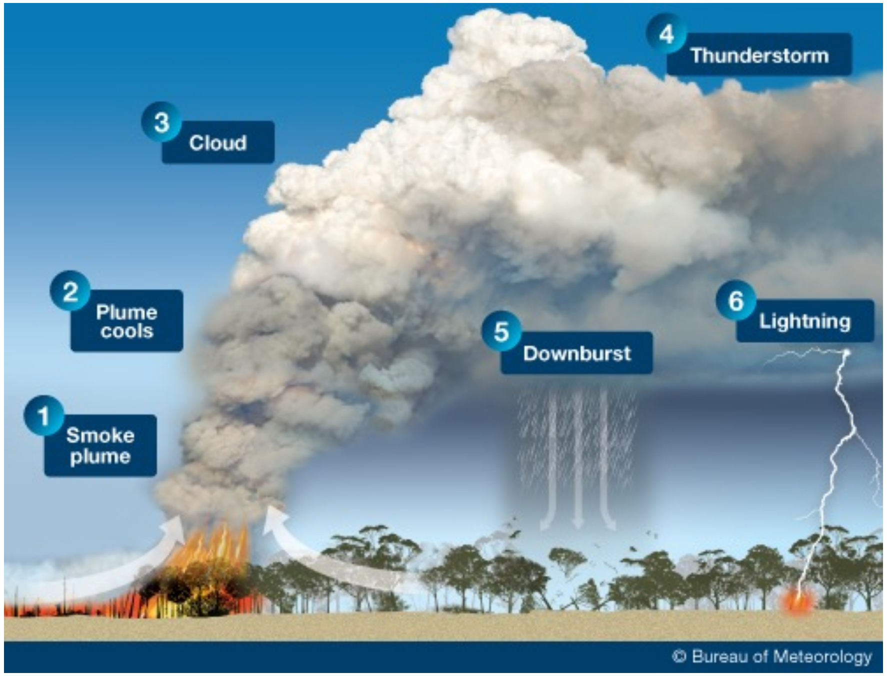
Equation of State:

$$p = (\gamma - 1)\left(E - \frac{m^2}{2\rho}\right)$$

Reisner, J., Serencsa, J., Shkoller, S. A space-time smooth artificial viscosity method for nonlinear conservation laws. Journal of Computational Physics, 235, 912-933, 2013.

Pyrocumulonimbus (PyroCb) Clouds

- Form by condensation of intensely heated, rising air becoming saturated due to adiabatic cooling
  - Lifting provided by buoyancy due to heat + moisture from fire + latent heat release from phase change
- Extent of pyroCb development depends on atmospheric stratification + ambient moisture + fire fluxes of heat and moisture
- Can produce lightning and precipitation
- Intense updrafts can carry significant quantities of smoke and aerosols into stratosphere

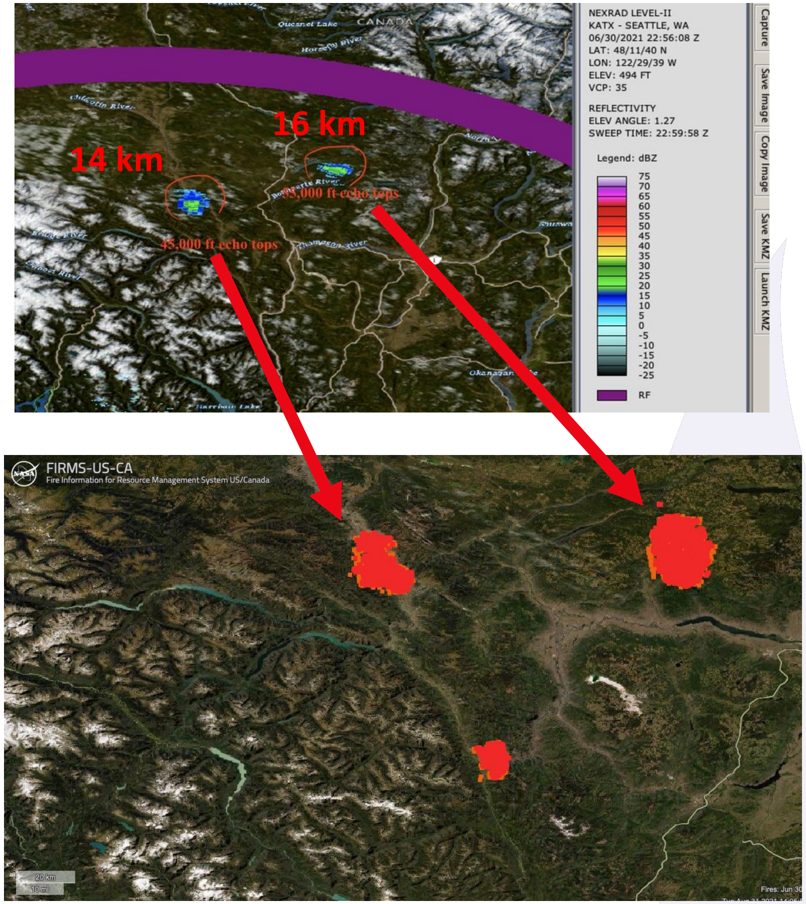


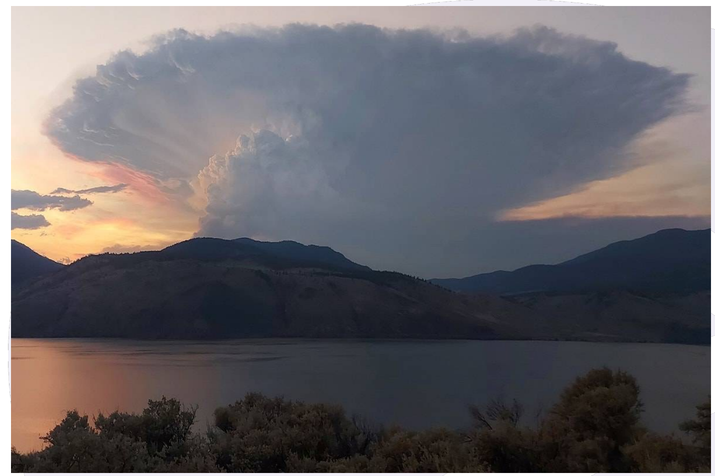
https://media.bom.gov.au/social/upload/images/pyrocumulus_Blog.png

Tory, K.J., Thurston, W.: Pyrocumulonimbus: A literature review. Bushfire and Natural Hazards CRC. Bureau of Meteorology, Australian Government. Report No. 3.26.067, 2015.

Why do we want to model PyroCbs?

- Motivation: Sparks Lake Fire, BC





Important to be able to capture microphysical processes in our numerical simulations to more accurately depict and study these phenomenon

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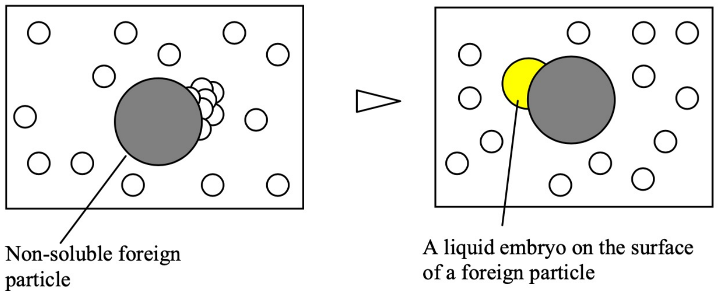
https://www.coastmountainnews.com/news/wildfire-north-of-kamloops-grows-to-20000-hectares-136-properties-evacuated/
https://firms2.modaps.eosdis.nasa.gov/usfs/map/#t:adv;d:2021-07-01;l:noaa20-viirs,viirs,modis_a,modis_t,country-outline;@-120.3,50.8,8z
https://twitter.com/nplareau/ http://bcfireinfo.for.gov.bc.ca https://www.vancouverislandfreedaily.com/news/wildfire-sparks-near-perimeter-of-devastating-2017-elephant-hill-fire/

Cloud Microphysics Overview

Heterogeneous Nucleation: water condenses onto micron and sub micron aerosol particles in the atmosphere that serve as "condensation nuclei"



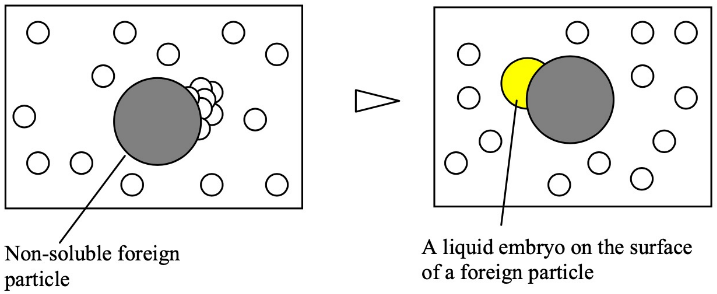
Sakrani, Samsudi & Jie, Lim & Yussof, Wahab. (2008). The formation of nanoscale clusters - nanofilms / quantum dots predicted using a capillary model of nucleation. Malaysian Journal of Fundamental and Applied Sciences. 1. 10.11113/mjfas.v1n1.12.
http://hogback.atmos.colostate.edu/cmmap/learn/clouds/cloudMicro3.html
https://bertram.chem.ubc.ca/ice-nucleation/

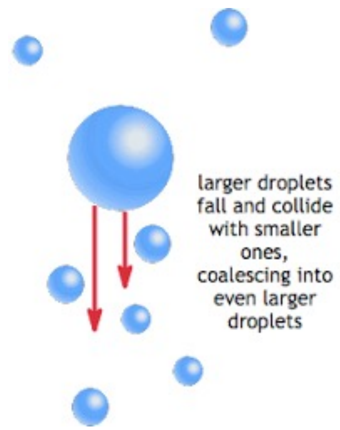
Cloud Microphysics Overview

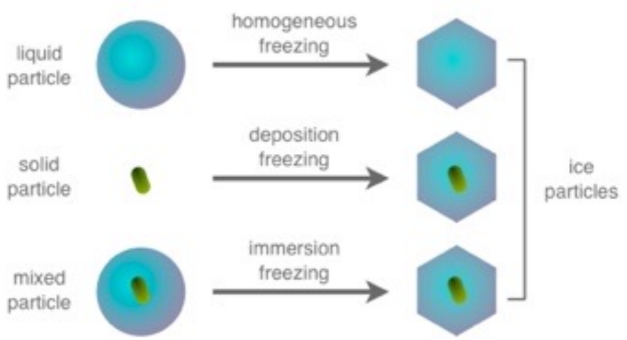
Heterogeneous Nucleation: water condenses onto micron and sub micron aerosol particles in the atmosphere that serve as "condensation nuclei"

Collision and Coalescence

Ice Crystal Formation and Growth







Sakrani, Samsudi & Jie, Lim & Yussof, Wahab. (2008). The formation of nanoscale clusters - nanofilms / quantum dots predicted using a capillary model of nucleation. Malaysian Journal of Fundamental and Applied Sciences. 1. 10.11113/mjfas.v1n1.12.
http://hogback.atmos.colostate.edu/cmmap/learn/clouds/cloudMicro3.html
https://bertram.chem.ubc.ca/ice-nucleation/

Cloud Microphysics Overview

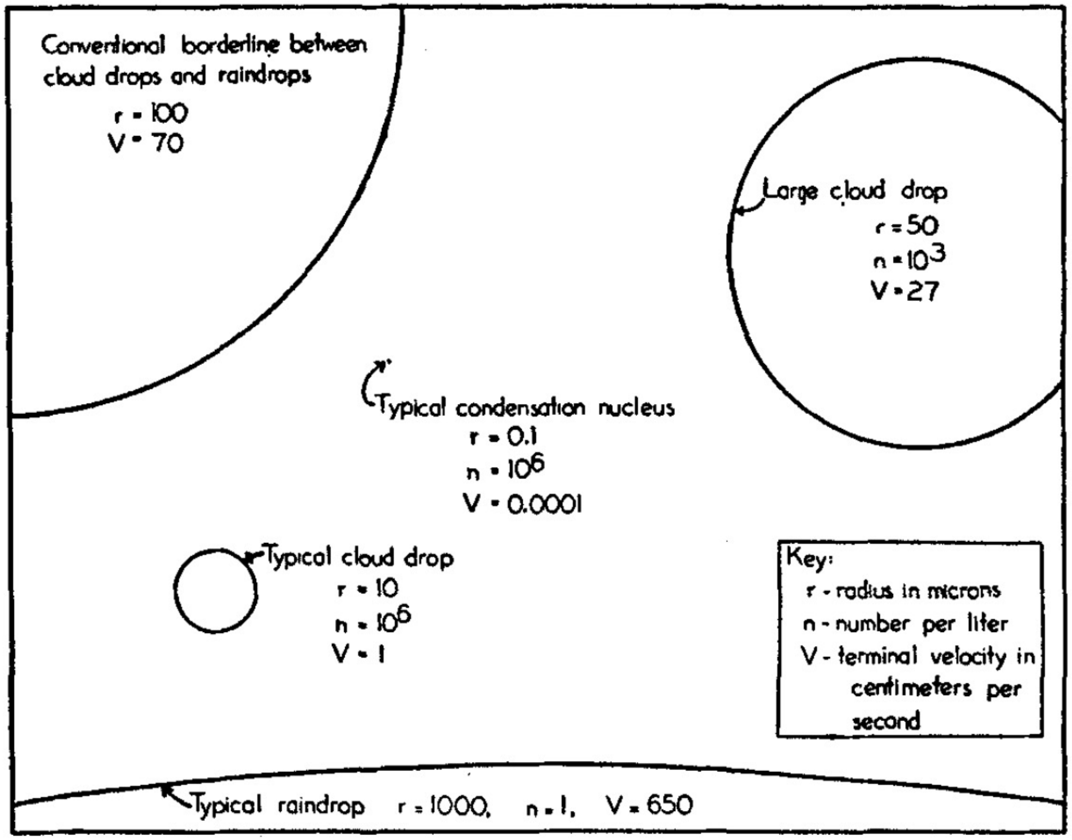


FIG. 2. Comparative sizes, concentrations, and terminal fall velocities of some particles involved in condensation and precipitation processes. Note particularly the great difference in radius of a typical cloud drop and of a typical raindrop.

McDonald, James E. The Physics of Cloud Modification, Editor(s): H.E. Landsberg, J.Van Mieghem, Advances in Geophysics, Elsevier, Volume 5, 1958, Pages 223-303, https://doi.org/10.1016/S0065-2687(08)60079-5.

Statement of Research Problem and Goals

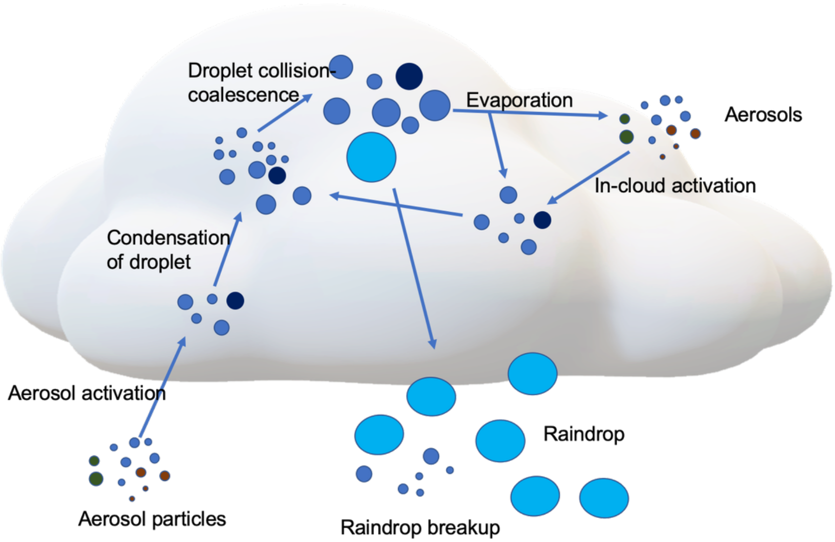
- Modeling development of clouds and precipitation processes involves sub-centimeter scale referred to as cloud microscale

- Most atmospheric models apply Eulerian approach for clouds with thermodynamics variables

- Most common and efficient method used today is Lagrangian Cloud Model (LCM)
  - Eulerian flow-field + Lagrangian framework to capture microphysics

Statement of Research Problem and Goals

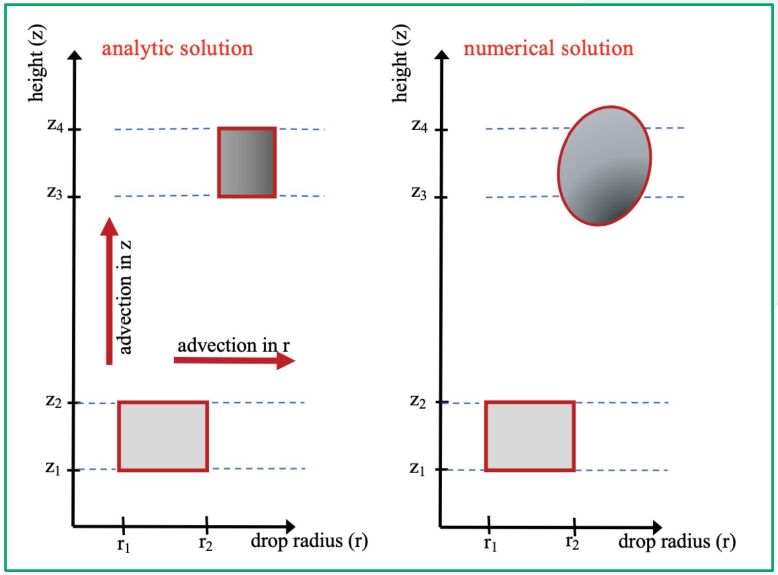
- Implement Lagrangian Cloud Model within HiGrad that can simulate the following microphysical cloud processes within a pyroCb event:
  - Aerosol (soot) production and tracking
  - Condensation of water onto aerosols as they rise
  - Evaporation of water droplets
  - Collision/coalescence of water droplets
  - Ice nucleation
  - Raindrop breakup



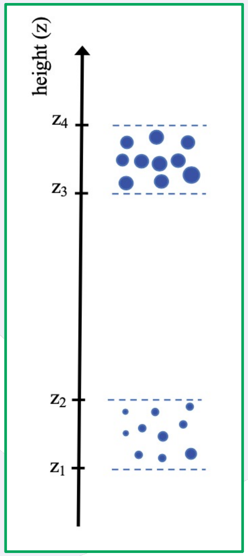
https://sisichenclouds.weebly.com/research.html

Why Lagrangian Cloud Microphysics

- Classic Eulerian Approach
  - Explicitly model evolution of particle size/mass distributions
  - Numerical diffusion leads to unphysical broadening of particle size distributions
  - Increasing complexity of microphysical interactions has not shown convergence of model results



- Lagrangian Approach
  - Combine group of cloud droplets with same properties into a superdroplet; track specific superdroplet's evolution in time
  - No numerical diffusion because transport in physical space and growth of droplets calculated individually using ODEs
  - Simulates relationship between aerosol and cloud droplet number concentration with accuracy compared to observed data



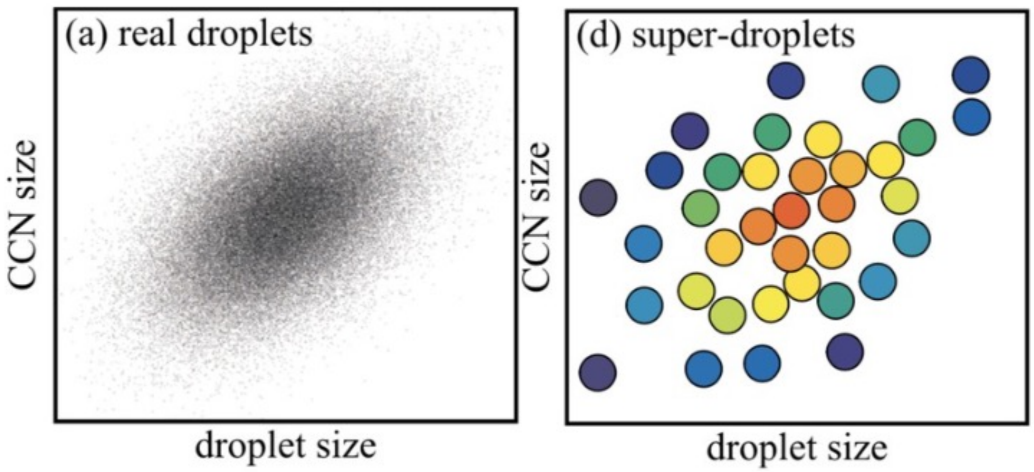
Grabowski W.W., Morrison, H., Shima, S., Abade, G. C., Dziekan, P., Pawlowska, H.: Modeling of Cloud Microphysics: Can We Do Better? Am. Meteo. Soc., 2019.

Lagrangian Cloud Microphysics

- Superdroplet Method (SDM): combines group of cloud droplets with same properties into a superdroplet (SD)

- Ensemble of SDs traced in physical space using model-predicted flow field and grown or shrink as they move with the flow

- SDs experience all cloud microphysical processes in the model



Grabowski W.W., Morrison, H., Shima, S., Abade, G. C., Dziekan, P., Pawlowska, H.: Modeling of Cloud Microphysics: Can We Do Better? Am. Meteo. Soc., 2019.

The Lagrangian Cloud Model: Activation + Condensation

Background aerosol: condensation nuclei not particularly of interest

Activation criteria: initialized as r = 1 micron superdroplets and immediately start growing

Condensation:

$$\boxed{\frac{dr}{dt} = \frac{GSF}{r}}$$

$G = \frac{1}{F_k + F_d}$ $\quad F_k = \left(\frac{l_v}{R_v T} - 1\right)\frac{l_v}{qT}$ Heat conduction term $\quad F_d = \frac{R_v T}{D e_S(T)}$ Vapor diffusion term

$D = (0.015T - 1.93)$ Diffusivity of water vapor

$e_S(T) = 6.112e^{\frac{17.67T}{T+243.5}}$ Saturation vapor pressure

$S = \frac{q_v}{q_{vs}} - 1$ Supersaturation

F Ventilation Factor (~ 1)

R_v	Moist gas constant
q	Thermal conductivity of moist air
T	Temperature
l_v	Latent heat of vaporization
q_v	Water vapor mixing ratio
q_{vs}	Saturation water vapor mixing ratio

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Andrejczuk, M., Reisner, J.M., Henson, B., Dubey, M.K., Jeffery, C.A. The potential impacts of pollution on a nondrizzling stratus deck: Does aerosol number matter more than type? Journal of GeophysicalResearch. 113(D19204), 1-17, 2008.

The Lagrangian Cloud Model: Activation + Condensation

Source aerosol: organic carbon and black carbon (soot)

Activation criteria: initialized as r = 100 nanometer superdroplets and start growing based on κ

Condensation:

$$\boxed{r\frac{dr}{dt} = \frac{D_{eff}}{\rho_w}(q_v - q_{vs}a_w(r, r_d, \kappa)exp\left(\frac{A}{r}\right))}$$

Effective Diffusion term:

$$\frac{1}{D_{eff}} = (D\rho_d)^{-1} + K^{-1}q_{vs}\frac{l_v}{T}\left(\frac{l_v}{R_vT} - 1\right)$$

Kohler term:

$$A = \frac{2\sigma_w}{R_vT\rho_w}$$

Water activity:

$$a_w(r, r_d, \kappa) = \frac{r^3 - r_d^3}{r^3 - r_d^3(1-\kappa)}$$

ρ_w	Density of liquid water
ρ_d	Density of dry air
D	Diffusivity of water vapor
K	Heat conduction term
T	Temperature
l_v	Latent heat of vaporization
q_v	Water vapor mixing ratio
r	radius
r_d	Dry radius
κ	Hygroscopicity parameter
q_{vs}	Saturation water vapor mixing ratio
σ_w	Surface tension of water
R_v	Moist gas constant

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Dziekan, P., Waruszewski, M., Pawlowska, H. University of Warsaw Lagrangian Cloud Model (UWLCM)1.0: a modern large-eddy simulation tool for warm cloud modeling with Lagrangian microphysics. Geo-science Model Development, 12, 2587-2606, 2019.

The Lagrangian Cloud Model

Background aerosol + Source aerosol

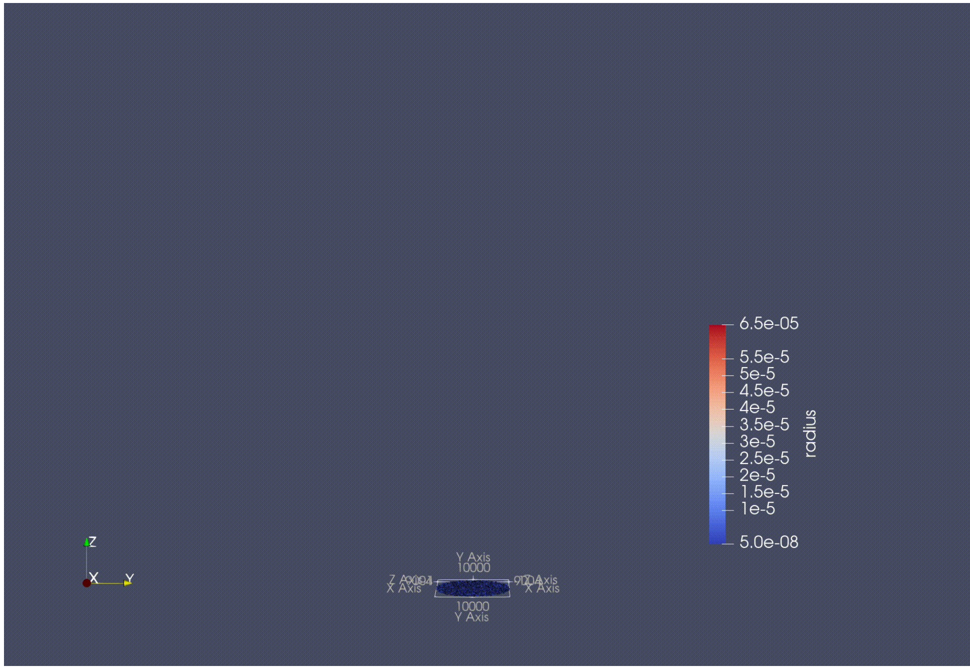
Evaporation criteria: (performed every timestep, for every superdroplet)

If $\frac{r_w - r_d}{r_d} < 0.01$, then evaporate

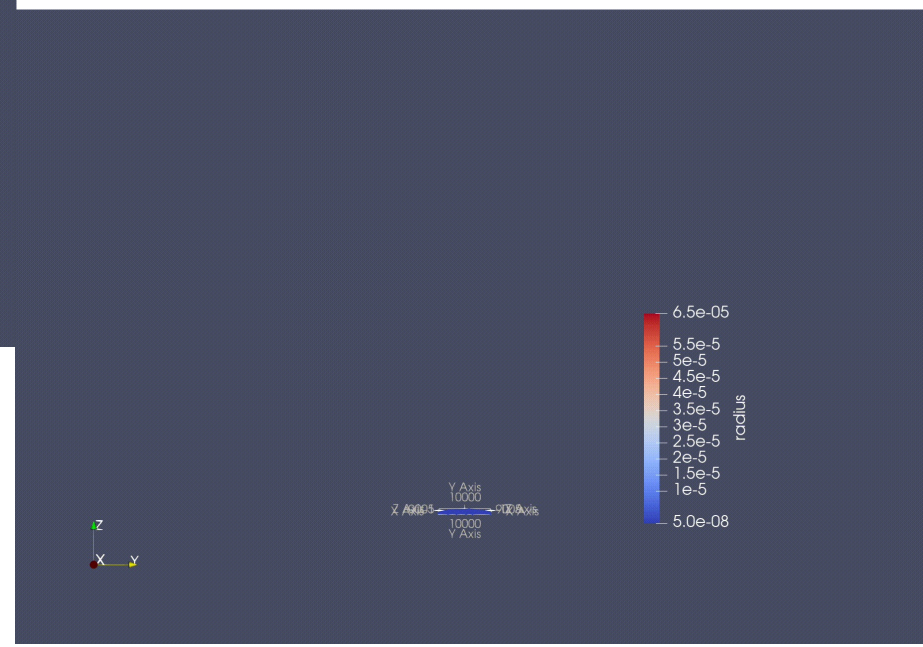
Multiplicity (m) values: how many real particles represented by superdroplet

$$9x10^{12} < m < 2x10^{14}$$

The Lagrangian Cloud Model Preliminary Results: Activation, Condensation, Evaporation



Cross section:



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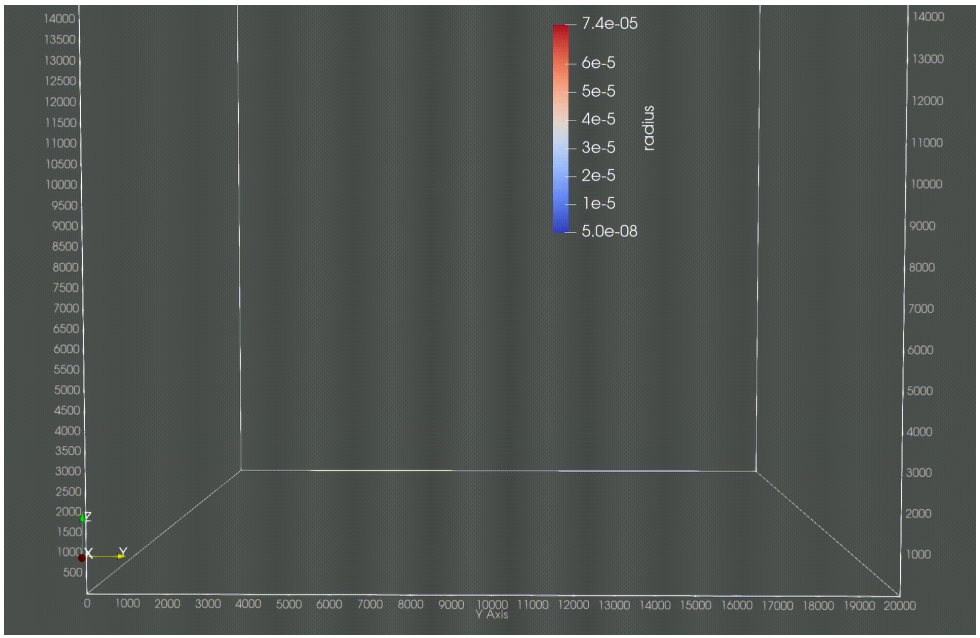
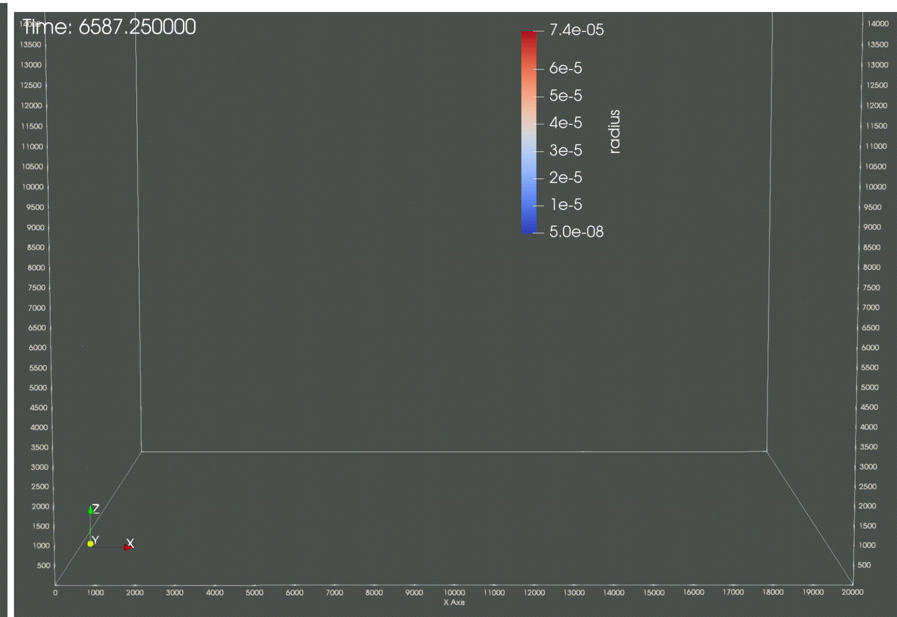
The Lagrangian Cloud Model Preliminary Results: Particle Tracking





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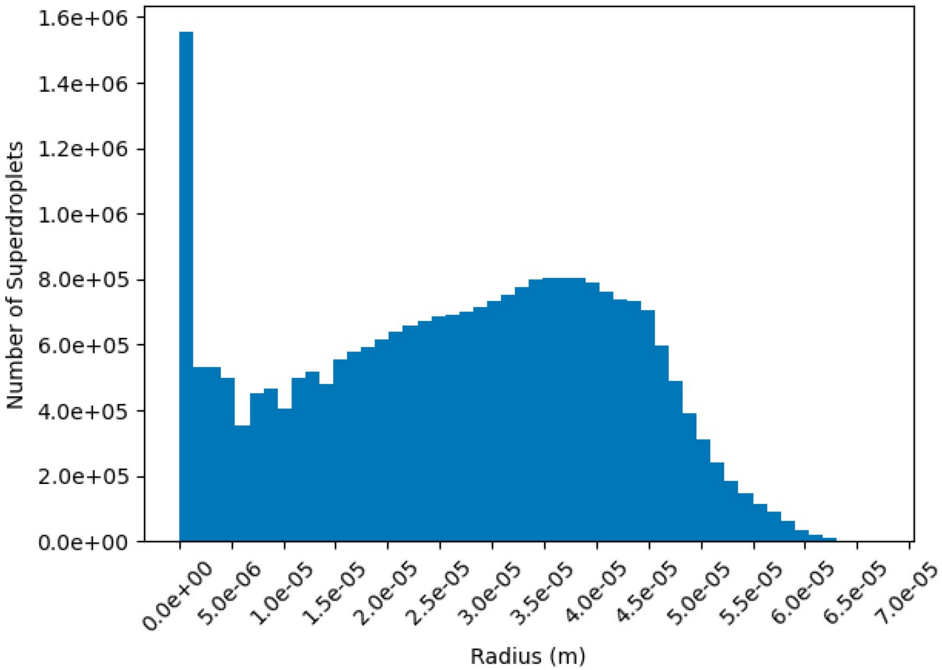
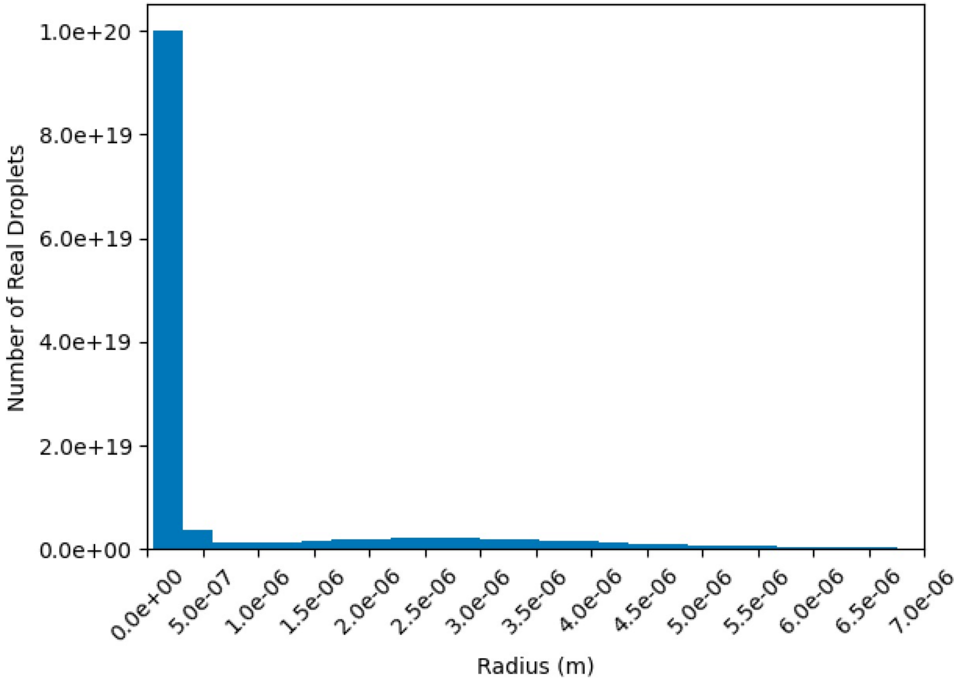
The Lagrangian Cloud Model Preliminary Results: Particle Size Distribution





Measurements from Literature	Cloud Droplet Diameter
2002 Amazon Deforestation Fires, Martins and Dias(2009)	< 30 microns
2018 Western US Fire Season, Twohy et al.(2021)	5 - 7 microns
2002 Amazon Deforestation Fires, Andreae et al.(2004)	< 40 microns
WRF Simulation Idealized Supercells, Kalina et al.(2014)	< 18 microns
WRF Simulation Deep Convective Systems in China, Xie et al.(2013)	5.5 - 9 microns
WRF Supercell Storm Simulation, Lim et al.(2011)	5 - 25 microns
Measurements of Supercell Thunderstorm in Montana, Musil et al.(1986)	< 30 microns

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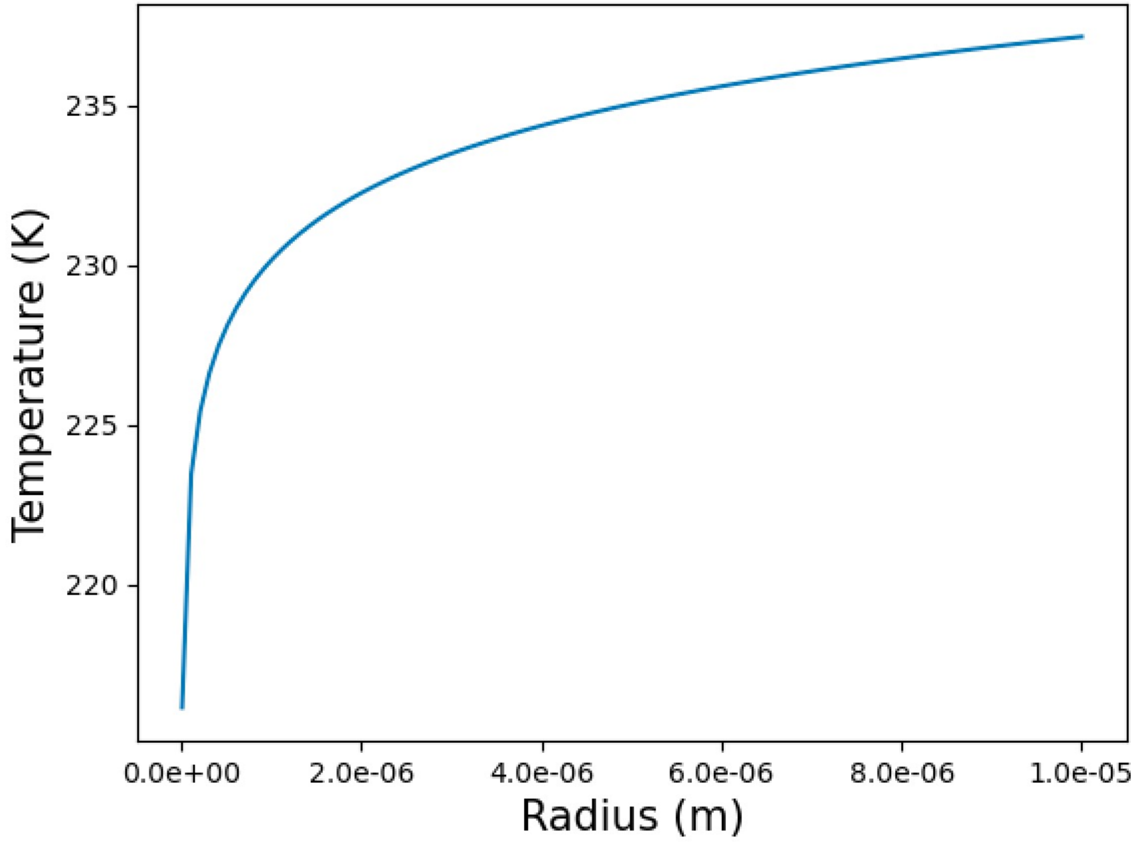
Next Step: Ice Microphysics

- Implement freezing of liquid cloud droplets according to



Future Work

- Ice microphysics
  - Important for initiation of precipitation
- Collision/Coalescence of droplets
  - Important for the formation of rain droplets
- Raindrop breakup
  - Important for modeling precipitation
- Soot liquid water content (LWC) for atmospheric chemistry applications
- Simulation of Sparks Lake Fire from BC 2021 Fire Season with all microphysical processes

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Thanks! Questions?

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Effective Diffusion term:

$$\frac{1}{D_{eff}} = (D\rho_d)^{-1} + K^{-1}q_{vs}\frac{l_v}{T}\left(\frac{l_v}{R_vT} - 1\right)$$

Latent heat of vaporization:

$$l_v(T) = l_{v0} + (c_{pv} - c_1)(T - T_0)$$

Kohler term:

$$A = \frac{2\sigma_w}{R_vT\rho_w}$$

Water activity:

$$a_w(r, r_d, \kappa) = \frac{r^3 - r_d^3}{r^3 - r_d^3(1-\kappa)}$$

Diffusivity of water vapor:

$$D = D_0\frac{1 + \frac{\lambda_D}{r}}{1 + 1.71\cdot\frac{\lambda_D}{r} + 1.33\cdot\left(\frac{\lambda_D}{r}\right)^2}$$

$$\lambda_D = 2D_0(2R_vT_w)^{-\frac{1}{2}}$$

Heat conduction term:

$$K = K_0\frac{1 + \frac{\lambda_K}{r}}{1 + 1.71\cdot\frac{\lambda_K}{r} + 1.33\cdot\left(\frac{\lambda_K}{r}\right)^2}$$

$$\lambda_K = \frac{4}{5}K_0\frac{T}{p}(2R_dT)^{-\frac{1}{2}}$$

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ρ_d	Density of dry air
D	Diffusivity of water vapor
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T	Temperature
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